LAWRENCE
LIVERMORE
NATIONAL
LABORATORY

UCRL-PROC-207291

Pressure Gradient Effects On Two-Dimensional Plasma Expansion

S. Moon, R. F. Smith, J. Dunn, R. Keenan, J. Nilsen, J. R. Hunter, J. Filevich, J. J. Rocca, M. C. Marconi, V. N. Shlyaptsev

October 18, 2004

The 9th International Conference on X-ray Lasers
Beijing, China
May 24, 2004 through May 28, 2004

Pressure Gradient Effects On Two-Dimensional Plasma Expansion

S. Moon, R.F. Smith, J. Dunn, R. Keenan, J. Nilsen, J. R. Hunter
Lawrence Livermore National Laboratory, Livermore, CA 94551

J. Filevich, J.J. Rocca, M.C. Marconi
NSF ERC for Extreme Ultraviolet Science and Technology and Department of Electrical and Computer Engineering, Colorado State University, Fort Collins, Colorado 80523

V.N. Shlyaptsev
University of California Davis-Livermore, Livermore, CA 94551

Abstract. Recent advances in interferometry has allowed for the characterization of the electron density expansion within a laser produced plasma to within 10 μm of the target surface and over picosecond timescales. This technique employs the high brightness output of the transient gain Ni-like Pd collisional x-ray laser at 14.7 nm to construct an effective moving picture of the two-dimensional (2-D) expansion of the plasma. We present experimentally measured density profiles of an expanding Al plasma generated through laser irradiation in a 14μm line focus geometry. Significant lateral expansion was observed at all times as well as a pronounced on-axis electron density dip. Detailed modelling with a 2-D plasma physics code gives good agreement to experimental observations. Large pressure gradients associated with the tight focal spot conditions are calculated to dominate in shaping the plasma density profile.

1. Introduction

Understanding the underlying physical processes driving the expansion of laser produced plasmas is of considerable practical and fundamental interest. Combining well characterized experimental observables with detailed simulations can give a quantitative measure of conditions within the plasma. Interferometry is a powerful tool for accurately diagnosing the two-dimensional (2-D) evolution of dense laser-produced plasmas. The recently developed technique of picosecond x-ray laser interferometry combines the short wavelength of the 14.7 nm Ni-like Pd laser with diffraction grating interferometer (DGI) instrumentation to enable the direct measurement of the electron density profile within a laser-produced plasma to within 10 μm of the target surface [1]. The picosecond duration of the x-ray laser probe pulse allows for an effective snapshot of the electron density profile while reducing the effects of plasma motion blurring at the ablation front. Also, the short wavelength, λ, and high brightness of the probe beam allows for characterization of large plasmas at high density with less deleterious effects from free-free absorption, $\propto \lambda^3(1- \exp[-hc/\lambda kT])$, and refraction ($\propto \lambda^2$) [1]. This technique produces a series of high quality 2-D density measurements providing unambiguous characterization of the time evolution in a fast evolving plasma for validation of existing 2-D hydrodynamic codes.

2. Experiment

The electron density evolution of a laser-heated Al plasma is measured using a diffraction grating interferometer (DGI) [2] at different times, relative to the peak of a 600ps plasma forming pulse. This gives an effective moving picture of how the plasma evolves in space and in time. The experimental results show pronounced two dimensional effects such as significant lateral transport and an on-axis density dip. We use 2-D hydrodynamic simulations in order to calculate the contributions of various physical mechanisms driving the plasma expansion. Density depressions have been observed before for high intensities laser drivers (pondermotive force [3]) and for lower intensities were the pumping pulse lasts for several nanoseconds (coronal x-ray ray heating [4]). For the plasma conditions explored here, simulations suggest that the on–axis density dip can be explained by rapid movement of material laterally due to the large pressure gradients set up by the tightly focused laser beam.

The Ni-like Pd 14.7 nm x-ray laser probe beam and the plasma to be studied were generated using three laser beams at 1054 nm wavelength from the COMET facility at LLNL [1]. Single pass saturated x-ray laser output of a few 10's of µJs was achieved with an optical pumping combination of a 600 ps long pulse (2 J, 2×10^{11} W cm^{-2}) and a 13 ps (5 J, 3.5×10^{13} W cm^{-2}) main heating pulse. The x-ray laser output was imaged and routed into a diffraction grating interferometer for plasma probing experiments. Recent temporal measurements [5] of the output of the Ni-like Pd x-ray laser have shown a ~4 ± 0.5 ps output for the pumping conditions detailed above. For interferometry this sets the time period over which the electron density is sampled. For a detailed description of the interferometer instrumentation see ref [2]. A plasma heated by up to 3J of energy in a 600 ps, 1054 nm pulse, corresponding to a maximum intensity of 1×10^{12} W cm^{-2}, was produced in one arm of the interferometer. A 3.2 mm long line focus with a 14 µm focal width, was generated on a polished 1mm long Al slab target using a combination of a cylindrical lens, f = -200 cm, and an off-axis paraboloid, f = 30 cm. The temporal profile of the 600ps plasma forming beam along with a cross section of the laser line focus are used as inputs into 2-D Lasnex simulations. The relative delay between the arrival of the x-ray laser probe pulse, to the peak of the plasma forming beam was measured to within 100 ps with a fast diode. The x-ray laser could probe the plasma in the temporal range of –1 ns to +2 ns relative to the peak of the 600 ps plasma forming pulse by adjusting a delay arm in the plasma laser beam. The line focus plasma was probed longitudinally by the x-ray laser, thereby minimizing uncertainties in the interpretation of the interferograms arising from plasma gradients along the probe path. The plasma was imaged with a magnification of ~22 by a 25 cm focal length spherical multilayer mirror and relayed to a thinned back-illuminated 1024 × 1024 CCD detector with 12.7 × 12.7 µm^2 pixels. Using the x-ray laser beam with no plasma present, high quality fringes, with visibility $V = (I_{max} - I_{min})/(I_{max} + I_{min})$ of 0.72 ± 0.12, were observed for a 700 × 500 µm^2 (H × V) region.

3. Results

Figure 1 shows a series of interferograms at different probing times relative to the peak of the plasma forming pulse. The electron density, n_e in cm^{-3}, is related to the measured fringe shifts as $N_{fringe} = 6.68 \times 10^{-20}\ n_e\ L$, where L is the length (cm) of the plasma being probed by the 14.7 nm x-ray laser [6]. For the 1mm plasma lengths described here, one fringe shift is equivalent to an electron density of 1.5×10^{-20} cm^3. An estimated uncertainty of 10 - 20 % in the determination of the reference fringes results in an error of $1.5 - 3 \times 10^{19} cm^{-3}$ in the electron density. An additional phenomenon that can introduce errors in plasma probing experiments is the extent to which the probe beam is deflected by refraction in the plasma medium. Raytracing [7] has shown that this effect is negligible for the density gradients and plasma lengths considered here. The contribution of bound electrons to the refractive index within the plasma is calculated to be negligible for the plasma conditions studied here.

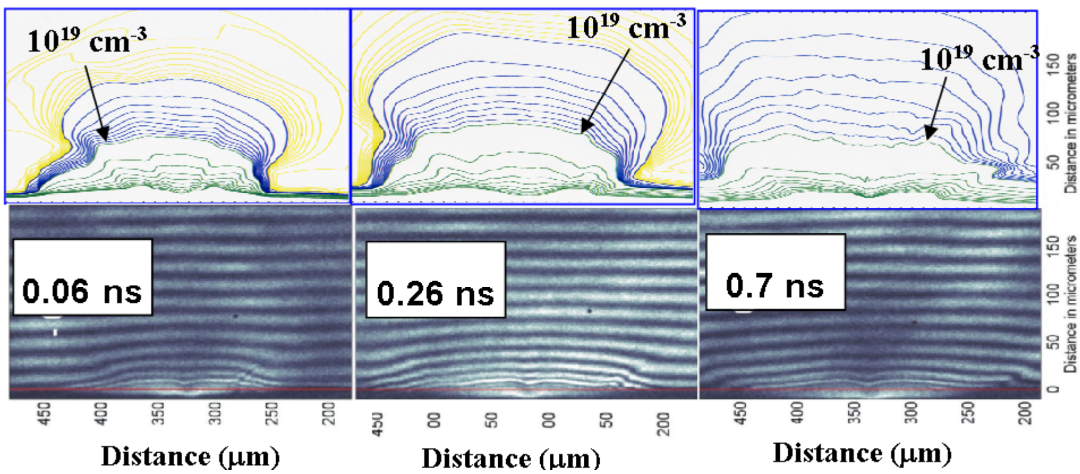

Fig 1. Experimentally obtained interferograms taken through longitudinal probing of an Al plasma at 0.06, 0.26 and 0.7ns after the peak of the 600ps plasma forming pulse. Strong lateral expansion is observed from the original 14μm focal spot. Less than 20μm from the target surface there is a clear formation of a depression in the free-electron density. Shown in the three contour plots above are the calculated two-dimensional electron density profiles from the LASNEX plasma physics code. The extracted electron density contour map is shown in a logarithmic scale with each line connecting regions of equal density. Experimentally obtained spatial and temporal profiles for the irradiation beam were used as inputs into the simulations. The simulations give good agreement for the 2D plasma expansion and show the existence of an on-axis density dip.

Significant lateral expansion from the initial 14 μm focal width is observed at all times. For all the interferograms the sideways expansion is symmetrical about the center of the focusing region. Within 10 μm from the target surface there is a pronounced dip in the measured on-axis electron density profile. The low irradiation intensities ($\sim 10^{12}$ W/cm^2) would suggest pondermotive forces could not explain such an effect [2]. Such a feature would be undetectable using traditional interferometric techniques which employed UV probe wavelengths due to severe refraction effects [7].

Also shown in Fig. 1 are contour plots of the electron density calculated from 2-D LASNEX [8] simulations. The experimentally determined temporal and spatial irradiation conditions were used as input into the code. Such modeling covers all phases of expansion leading to a plasma size much larger than the focal spot. With the 2-D simulations we have looked at several potential different driving mechanisms behind the plasma lateral expansion. Our preliminary findings suggest the dominant mechanism driving the evolution of the plasma is the strong pressure gradients set up by the tight line focus. By increasing the line focus to 50μm FWHM the on axis density dip is not observed.

Picosecond x-ray laser interferometry is a valuable technique in diagnosing plasma evolution within laser produced plasmas. The short sampling time of the probe beam reduces blurring effects and allows for probing to within 10μm of the target surface. In addition, the short wavelength probe minimizes effects associated with refraction and free-free absorption making this diagnostic well suited for studying large, fast evolving, dense plasmas. It has been shown that for the experimental conditions reported within this paper lateral expansion is a significant effect. Two-dimensional plasma physics codes are therefore necessary to model such experiments.

The support of Al Osterheld and Andy Hazi is greatly appreciated. The authors are pleased to acknowledge the technical contributions from Carl Bruns and Al Ellis. This work was performed under the auspices of the U.S. Dept. of Energy by the University of California Lawrence Livermore National Laboratory, through the Institute for Laser Science and Applications, under Contract No. W-7405-Eng-48 and by US Department of Energy Grant No. DE-FG03-98DP00208. This research was sponsored by the National Nuclear Security Administration under the Stewardship Science Academic Alliances program through DOE Research Grant # DE-FG03-02NA00062. The CSU researchers also gratefully acknowledge the partial support of the NSF ERC Center for Extreme Ultraviolet Science and Technology, award number EEC-0310717 and the W.M. Keck Foundation.

References

[1] Smith R F, Dunn J, Nilsen J, Shlyaptsev V N, Moon S, Filevich J, Rocca J J, Marconi M C, Hunter J R, and Barbee T W, Jr., Phys. Rev. Lett., **89** (6), 065004-1 (2002).

[2] Filevich J, Rocca J J, Marconi M C, Smith R F, Dunn J, Keenan R, Hunter J R, Moon S J, Nilsen J, Ng A, Shlyaptsev V N, “Picosecond resolution soft x-ray laser plasma interferometry”, J. Appl. Phys., vol. 43, No. 19 (2003); Filevich J, Kanizay K, Marconi M C, Chilla J L A, and Rocca J J, "Dense plasma diagnostics with an amplitude-division soft-x-ray laser interferometer based on diffraction gratings" Opt. Lett. 25, 356=96358 (2000).

[3] Wilks S et al., Phys. Rev. Lett. **73**, 2994 (1994).

[4] Filevich J, Rocca J J, Jankowska E, Hammarsten E C, Kanizay K, Marconi M C, Moon S J, Shlyaptsev V N, “Two-dimensional effects in laser-created plasmas measured with soft-x-ray laser interferometry”, Phys Rev E, vol.67, no.5, pp.56409-1-6. (2003).

[5] Dunn J et al., submitted to Optics Letters (2004).

[6] Da Silva L B, Barbee T W, Jr., Cauble R, Celliers P, Ciarlo D, Libby S, London R A, Matthews D, Mrowka S, Moreno J C, Ress D, Trebes J E, Wan A S, and Weber F, Phys. Rev. Lett. **74**, 3991-3994 (1995).

[7] Smith R F, Shlyaptsev V N, Dunn J, Nilsen J, Hunter J R, Rocca J J and Filevich J, Marconi M C, “Refraction Effects on X-ray and UV Interferometric Probing of Laser Produced Plasmas”, JOSAB, vol.20, no.1, Jan. 2003, pp.254-9. (2002).

[8] Zimmerman G B and Kruer W L, Comments Plasma Phys. Controlled Fusion **2**, 51-61 (1975).